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SEARCHING FOR CYGNETS*

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ABSTRACT

The reported observation in underground detectors of high-energy muons from the direction of the compact binary X-ray source CYG X-3 (2030+4047) cannot be explained by conventional physics. In this paper some explanations for the effect based upon unconventional physics are reviewed.

Cygnus X-3 is believed to be a compact X-ray source in the Cygnus constellation. It is observed to be a very robust source of radiation from infrared to UHE (ultra high energy, E > 1 TeV). All radiation above infrared is modulated with a 4.8 hour period. This 4.8^h period is thought to be the orbital period of a binary system composed of a neutron star and a companion star of about 4 $M_\odot$.

The observed spectrum of radiation from CYG X-3 can be fit by a single power law over 13 decades in energy, from 10^3 eV to 10^{16} eV:[1)]

$$\frac{dN_\gamma}{dE} = 3\times10^{-10}\left(\frac{E}{1\,\mathrm{TeV}}\right)^{-2.1}\ \mathrm{cm^{-2}s^{-1}TeV^{-1}}. \qquad (1)$$

This spectrum has roughly equal luminosity per decade of energy. Assuming a distance of 12 kpc, the total luminosity of CYG X-3 above 1 GeV is in excess of 10^{38} erg s^{-1}, making it the brightest γ-ray source in our galaxy.

It is possible to construct an astrophysical model for the CYG X-3 system by using the phase information of the radiation. A 'theorist's rendition' of the phase information is shown in Figure 1. The origin of the X and γ rays is thought to be the neutron star, and

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the minimum of the X-ray and γ-ray radiation occurs when the neutron star is eclipsed by the main sequence star between phase -0.25 and +0.25. The absence of a zero-flux minimum for the X-rays can be understood if there is a cocoon of optical depth order unity for X-rays surrounding the system. The cocoon can back scatter X-rays during the eclipse, giving a reduced, but non-zero, X-ray flux. The cocoon will be transparent to γ-rays, giving a zero minimum γ-ray flux during eclipse. As seen in Figure 1, the UHE radiation has a 4.8^h period, but a phase structure much different than the X-rays or γ-rays. Vestrand and Eichler[2)] and also Stecker[3)] and Stenger[4)] have used the phase structure to model the UHE emission. They assume the pulsar is a source of an energetic beam of primary protons. The primary protons hit the star and produce secondary π^0's (among other things), which decay to the γ's detected as the UHE flux. This mechanism will produce detectable UHE γ's if the primary beam passes through enough material to produce π^0's but not enough material to completely absorb the γ's from π^0 decay. This condition will be met for only a small fraction of the orbital period, around $\psi = \pm 0.25$ when the neutron star is at grazing incidence. The primary proton beam is not detected because it is dispersed by galactic magnetic fields before reaching the solar system. Models of the acceleration mechanism for the primary beam are quite complicated. They are thought to involve large $\vec{v} \times \vec{B}$ electric fields in the vicinity of the pulsar, but a completely self-consistent picture for the acceleration mechanism is very difficult to construct.[5)] Most of our results will be independent of the details of the acceleration mechanism of the primary beam.

In order to understand the signal for new physics it is first necessary to calculate the expected flux of neutrinos from CYG X-3. The calculation reported here was done by several groups with very similar results.[6,7)] The basic assumption is that the primary beam makes charged mesons, in addition to the neutral mesons, in the collision with the star. The decay of the charged mesons will result in a neutrino flux from the system.

If the UHE γ-rays originate from a source spectrum with the power law form

$$\frac{dS_\gamma}{dE_\gamma} = AE^{-n} , \tag{2}$$

the π^o source spectrum should be of the form

$$\frac{dS_{\pi^o}}{dE_\pi} = A\ 2^{n-1}E^{-n} , \tag{3}$$

where the factor 2^{n-1} is from 2 photons of energy $E_{\pi^o}/2$. There should be $\pi^\pm$'s produced also, and the source spectrum for the $\pi^\pm$'s should be

$$\frac{dS_{\pi^+ + \pi^-}}{dE_\pi} = 2^n AE^{-n} = 2^n \frac{dS_\gamma}{dE_\gamma} . \tag{4}$$

The energy of the neutrinos produced by $\pi^\pm$ decay will depend upon whether the $\pi^\pm$'s decay in flight or interact before decay. If the $\pi^\pm$'s decay in flight the neutrino source spectrum should be related to the photon source spectrum by

$$\frac{dS_\nu}{dE_\nu} = (1-m_\mu^2/m_\pi^2)^n \frac{dS_\gamma}{dE_\gamma} . \tag{5}$$

Propogation of the neutrino and photon source spectra through the star will result in the flux detected terrestrially. The absorption of neutrinos and photons depends upon the material seen by the particle traversing the star, which, in turn, depends upon the phase of the orbit. The γN cross section at high energies is nearly energy independent, so the phase structure of UHE photons should be energy independent. Unlike photons, the neutrino cross section is proportional to the energy (for E_ν < 100 TeV), and the phase diagram for the neutrino flux will depend upon E_ν. The neutrino light curve found by propagating neutrinos through a $4M_\odot$ main sequence star is shown in Figure 2. It should be remembered that the relative flux is shown in Figure 2 - the absolute flux relating different energies falls as $E^{-2.1}$. The details of the phase structure is most sensitive to the central density of the star. Observation of the neutrino light curve would offer a unique tool to probe the central density of the star.

In the above calculations we have assumed the mesons decay before interacting. Since the decay length of the mesons is proportional to E/m, sufficiently energetic mesons will decay before interacting, and neutrino production will be via a beam dump mode. The decay lengths of $\pi^{\pm}$ and $K^{\pm}$ in the star are

$$(\gamma c\tau)_{\pi^{\pm}} = 5\times10^{6}\ (E/1\ \mathrm{TeV})\mathrm{cm}$$
$$(\gamma c\tau)_{K^{\pm}} = 8\times10^{5}(E/1\ \mathrm{TeV})\mathrm{cm} \qquad (6)$$

The cross section for interaction of the mesons is about 3×10^{-26} cm^2 at $E > 1$ TeV. The typical density in the envelope of the star is about 10^{-6}g cm^{-3}, so we parameterize the envelope density as $\rho = 10^{-6}\rho_{-6}$g cm^{-3}. There will be a threshold energy above which the mesons will decay before interacting, given by

$$E_T = \begin{cases} 300\ (\rho_{-6})^{-1}\ \mathrm{TeV} & (K^{\pm}) \\ 30\ (\rho_{-6})^{-1}\ \mathrm{TeV} & (\pi^{\pm})\ . \end{cases} \qquad (7)$$

The existence of this threshold should result in a feature in the neutrino spectrum at E_T, providing a unique tool to examine the density of the stellar envelope.

Using the observed UHE photon spectrum and phase width, the phase-averaged neutrino flux is expected to be

$$\frac{dN_{\nu}}{dE} = 2\times10^{-10}\left(\frac{E}{1\mathrm{TeV}}\right)^{-2.1}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \qquad (E < E_T)$$

$$= 2\times10^{-12}\left(\frac{E}{1\mathrm{TeV}}\right)^{-2.1}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \qquad (E > E_T). \tag{8}$$

The normalization of the neutrino flux is uncertain by at least an order of magnitude due to uncertainties in the photon phase width, absorption of photons, etc. However the normalization is unlikely to be off by more than two orders of magnitude, and the slope of the power law spectrum should be close to -2.1.

The neutrino flux can be detected in underground detectors either by observing a $\nu_\mu \rightarrow \mu$ conversion in the detector (which we call a contained event) or by observing a muon from a $\nu_\mu \rightarrow \mu$ conversion in the surrounding rock passing through the detector (which we call an external event). The probability that the neutrino converts in a detector of linear dimension $\ell \approx 10$ m is given by (all distances in the paper are given in terms of water equivalent)

$$\begin{aligned} P_c &= n\sigma\ell \\ &= 4\times10^{-9}(E/1\ \mathrm{TeV}) \qquad (E \lesssim 100\ \mathrm{TeV}) \\ &= 7\times10^{-8}\ \ell n(E/1\ \mathrm{TeV}) \qquad (E \gtrsim 100\ \mathrm{TeV}), \end{aligned} \tag{9}$$

where σ is the cross section for $\nu_\mu N \rightarrow \mu^- + X$ (for simplicity we have assumed equal cross section for ν and $\bar{\nu}$). The event rate for contained events is given by

$$\begin{aligned} \Gamma_c &= A_D \int P_c \frac{dN_\nu}{dE}\, dE \\ &= 6\times10^{-12}\left(\frac{E_{min}}{\mathrm{GeV}}\right)^{-0.1}\ \mathrm{sec}^{-1} \end{aligned} \tag{10}$$

where E_{min} is the larger of the detector threshold and the low energy cutoff in the neutrino spectrum, and A_D is the detector area, assumed to be $4\times10^6\mathrm{cm}^2$.

The probability that a neutrino interacts in the earth and produces a muon which passes through the detector depends upon the range of the muon. With a muon energy loss rate of

$$-\frac{dE}{dX} = 1.9\times10^{-6}\ \mathrm{TeVcm}^{-1} + 4\times10^{-6}\ \mathrm{cm}^{-1}\ E\ , \tag{11}$$

the range of the muon is

$$R(E) = 3\times10^{5}\ \ln(1 + 2E/1\mathrm{TeV})\mathrm{cm}. \tag{12}$$

For external events, the range of the muon replaces the detector linear dimension in Eq. (9). If we assume the muon has half the incident neutrino energy, then the probability of an external event is

$$P_E = 10^{-6}\ (E/1\mathrm{TeV})\ \ln(1 + E/1\mathrm{TeV}). \qquad (E < 100\ \mathrm{TeV}) \tag{13}$$

Notice that for E greater than a few GeV, $P_E > P_C$. The rate for external events is

$$\Gamma_E = A_D \int P_E \frac{dN}{dE}\ dE$$

$$= 3\times10^{-8}\ \mathrm{sec}^{-1}. \tag{14}$$

The fact that the external events dominate the contained events is a result of the slope of the spectrum. The total detection rate is about one per year, but as discussed above, that estimate could be off by one or possibly two orders of magnitude. For the external events, the effective size of the target is limited either by the muon range, or by the distance to the surface of the earth. It is clear that as the zenith angle of CYG X-3 increases, the muon signal due to primary neutrinos should not decrease.

Recently two experimental groups. Soudan and NUSEX, have reported an excess of high energy muons from the direction of CYG X-3, with a distribution of arrival times modulated with a 4.8^h period. The number of muons seen by the experiments, 84 ± 20 events in 0.96 years in Soudan and 32 events in 2.4 years in NUSEX, is much larger than the above estimates for neutrino-induced events, if one takes into account the relatively small size of the detectors. In fact, the detected muon flux is comparable to the total "photon" flux. The most striking characteristic of the signal is that the muons are not seen at large zenith angles. The zenith angle dependence of the signal strongly suggests that the muons have an atmospheric origin (or perhaps an origin in the first few hundred meters of rock). The Soudan and NUSEX results seem to confirm previous results from the Kiel air shower experiment[10)] of excess muons in the air showers from CYG X-3. The magnitude and zenith angle dependence of the muons rule out neutrinos as a source of the muons. If the primary particles in the air showers are photons, conventional calculations of muon production in the shower cannot account for the observed muon flux.[11)] (Even if the air shower primaries are protons, the observed underground muon flux is too large to be accounted for by the observed air shower flux.[12)])

The data suggest that the initiating particle must: 1) be neutral, in order to reach the solar system without being dispersed by galactic magnetic fields; 2) be light (less than a few GeV), in order to keep phase coherence with the photons over the 12 kpc distance to CYG X-3; 3) be long-lived, with a lifetime greater than weeks or months depending on γ; 4) shower in the atmosphere like a hadron, i.e., produce muons efficiently; and 5) have a flux comparable to the air shower flux of $3\times10^{-10}(E/1\mathrm{TeV})^{-2.1}$ cm^{-2} sec^{-1} TeV^{-1}. It is clear that the above profile for a particle cannot be fit by any known particle. The unknown particle postulated to fit the above profile has been given the name cygnet.[16)] In the rest of this paper I will mention some recent proposals for cygnet candidates.

QUARK NUGGETS[12,13)] It is conceivable that there is a separate, stable phase of matter at greater than nuclear matter density. Quark nuggets would have a very small Z/A ratio, and can exist as a stable hadronic system with large A. It is not inconceivable to imagine the neutron star is, in fact, a quark star, and a source of quark nuggets.

A problem with this scenario is that the conventional quark nuggets are only stable for large A, and are probably too massive to account for the phase coherence. Quark matter does lead to an enhancement over normal nuclear matter in muon production when the primary showers in the atmosphere. But the enhancement is only about a factor of two.[12)]

<u>R-ODD PARTICLES FROM SUPERSYMMETRY</u>[14,15)] In supersymmetric theories with an unbroken R-parity, the lightest R-odd particle is stable. The photino is a good candidate for the lightest R-odd particle. It has been proposed that gluinos are produced in pp collisions along with the neutral and charged mesons responsible for the γ and ν flux. The gluinos will decay to photinos before interacting. If threshold for gluino production is low enough, which requires gluino masses less than a few GeV, the photino flux from CYG X-3 could be comparable to the photon flux at high energies. Although the photino would be a relatively light, neutral, stable particle, there are problems with this scenario. First, the photino most likely will not interact in the atmosphere, and the zenith angle dependence for muons produced by photino primaries should probably resemble that for neutrinos. Second, the mass needed to push threshold for gluino production low enough for an appreciable photino flux is very close to being ruled out by experimental data, if it has not already been ruled out. Although photinos are unlikely to be cygnets, they may prove to be detectable in future underground experiments.

<u>H-PARTICLES</u>[16)] The H-particle proposed by Jaffe[17)] is a metastable neutral strange dibaryon. The H would be a tightly bound six quark state (uuddss). The color-spin wavefunction of the H is the most symmetric, which should maximize the QCD hyperfine interaction leading to a more attractive potential than in other dibaryon systems. If the mass of the H is below $p\Lambda$ threshold, the H can only decay via double beta decay, and can have a lifetime long enough to reach the solar system from Cygnus. The H is almost unique in matching the first four profiles for a cygnet. Whether the H flux can be comparable to the total air shower flux depends upon the mechanism for cygnet production. If the incident beam from the neutron star is a

proton beam, H production will be suppressed, as the pp $\rightarrow$ HX cross section is smaller than the pp $\rightarrow$ πX cross section because it is necessary to create two units of strangeness and an $A = 2$ system. Under these conditions, it is difficult to imagine an H flux comparable to the Υ flux. If, however, the primary beam has a large strangeness fraction and consists of particles with $A > 1$, then there will not be any large supression factors in H/Υ production, and the flux of cygnets could be a large fraction, perhaps O(1), of the total air shower flux.

There are several potential problems with the H explanation for cygnets. The mass of the H may not be below pΛ threshold (or, perhaps, not even below $\Lambda\Lambda$ threshold). The mass of the H is a question that can be settled by experiment. Even if the H flux is comparable to the total air shower flux, the secondary muon flux would be smaller than that reported by a factor of 2-10. This is a problem for any explanation of the observation, not just for the H scenario. One possible reason for the discrepancy could be an intrinsic variability in the source. The astrophysical environment of CYG X-3 is much more complicated than the simple picture presented here. If anything, it is surprising that the system is as stable as observed. The flux may change between the measurements of the air shower flux and the detection of the underground neutrinos. Finally, there is no explanation for the angular spread seen in the data. The NUSEX signal is seen in a $10° \times 10°$ window in celestial coordinates, much larger than the $0.5°$ expected angular resolution. Again, this is a problem for any explanation of the signal.

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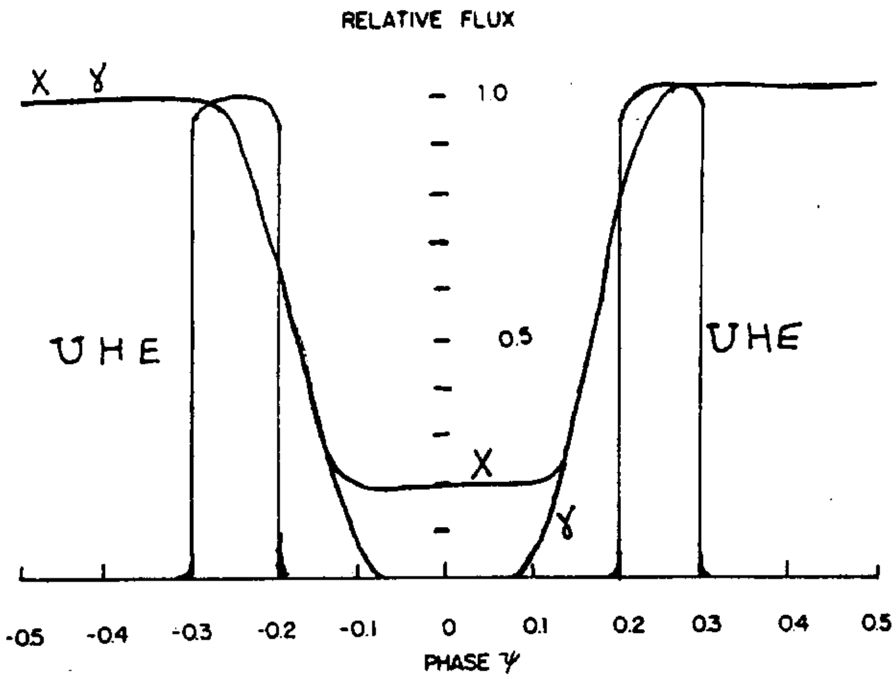

FIGURE 1 PHOTON FLUX

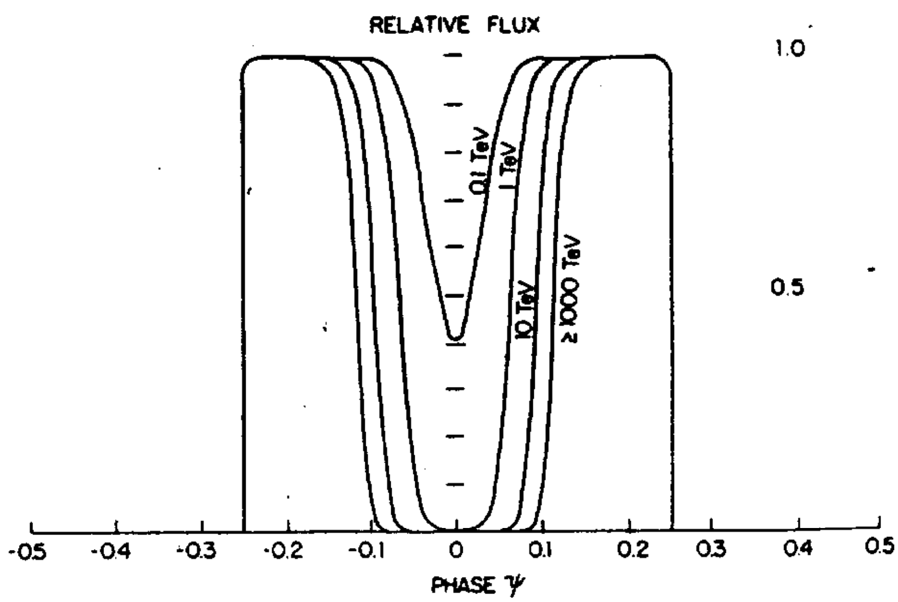

FIGURE 2 NEUTRINO FLUX